Isotonic dynamometry for the assessment of power and fatigue in the knee extensor muscles of females

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Summary

Impairments in muscle power production and recovery following short-duration intense activity could lead to decreased performance and risk of injury. We developed a power test for the knee extensor muscles using torque–velocity testing and moderate isotonic loads. Twenty-eight female volunteers performed three maximal efforts at each of four isotonic loads (27·1, 40·6, 54·2 and 67·8 N · m). If the calculated regression line for the torque–velocity data had an $r^2 \geq 0{\cdot}95$ (i.e. an acceptable test), maximal power (408 ± 56 W) was computed from the data. Immediately after torque–velocity testing, the subjects repeated maximal effort knee extensions with 33·9 N · m for three bouts of 15 repetitions with 15 s of rest to produce muscle fatigue, defined as a decrease in power output during isotonic exercise. After a 4 min rest, the torque–velocity test was repeated and power calculated (345 ± 48 W). For the group, the recovery of maximal power after the fatigue protocol was 85%. The extremes were represented by one subject who recovered only 70% of her maximal power and another who recovered completely (>98%). Physiological differences in muscle power following repeated exercise could have an impact on the outcome of therapeutic interventions for sports injuries, fatigue syndromes and occupational over-use conditions.

Keywords: exercise testing, human muscle, muscle power.

Introduction

Historically, human muscle testing involved measurement of the maximum force or the strength of muscles (Sale, 1991). Using such strength measurements as a reference point, rehabilitation programmes often emphasized exercising muscles at their maximum force capacity. It was assumed that strong muscles were also more powerful muscles. However, maximal power development occurs at velocities where force is moderate (Edgerton *et al*., 1986). Also, the development of peak velocity is limited due to the finite shortening range of the muscles. This restricted range of shortening imposes a time limitation on the muscles' ability to produce maximal velocity. Thus, for maximal power output of muscles, force must be produced quickly – a function of both neural activation and muscle contraction velocities. As a result, it is quite possible for a subject to test normal for muscle strength as measured by isometric, isokinetic or manual muscle testing and still be markedly deficient in muscle power production.

If the ability to develop or sustain maximal power has a different physiological basis than muscle strength, isokinetic, isometric or manual muscle testing may not be sufficient to determine whether a person has a performance deficit. One noteworthy problem after injury or immobilization is the lack of optimal neural activation due to pain or even slight joint effusion (Arvidsson *et al*., 1986). Since muscles must be activated quickly to produce maximal power, reduced muscle activation would be expected to reduce muscle power more than muscle strength. For upper body muscles, differences in neural activation have been reported for isometric and dynamic movements (Murphy & Wilson, 1996).

Although maximal power measurements have been made in man during running, jumping and cycling, assessments of power output during simple movements in healthy humans are rare (Moritani, 1992), and non-existent in patients with sports injuries, neuromuscular diseases, metabolic disorders or over-use syndromes. The development of muscular power and the ability to sustain it is of great importance to human endeavours in sports events, industrial tasks, and activities of daily living. The present work assessed maximal power output of the knee extensor muscles of college-aged females using an isotonic dynamometer (Richards *et al.*, 1996). It was hypothesized that, if maximal power could be measured during simple movements: (1) high power output would rapidly consume energy reserves much the same as an ischaemic exercise test would (Blei *et al.*, 1993), and (2) recovery of power following fatigue would identify individuals with differences in bioenergetics which could account for differences in work capacity.

Methods

Subjects

Twenty-eight healthy college-aged females (height 1·66 ± 0·06 m; weight 58·5 ± 5·4 kg) took part in the study after giving written informed consent, filling out an activity questionnaire and passing a screen for musculoskeletal problems. The activity questionnaire was used to eliminate exercise-trained individuals from this study. The project was approved by the West Virginia University Institutional Review Board for the Protection of Human Subjects.

Test protocol

The subjects were tested in a seated position with the legs flexed at 1·57 radians at the hip and 1·75 radians at the knee. The left knee was aligned with the mechanical axis of rotation of a dynamometer (Dynatrac™, Baltimore Therapeutic Equipment Co., Hanover, Maryland, USA). The left lower leg was loaded by a pad placed on the lower shin. The dynamometer is capable of providing a controlled load (isotonic pre-load) to limbs for both concentric and eccentric muscle actions (Richards *et al.*, 1996). Since the load is held constant, a maximal voluntary effort during concentric muscle actions results in a peak velocity of limb movement which is load-dependent. Since a spinning motor controls the eccentric muscle action, the velocity is limited for eccentric muscle actions by the motor speed (6·4 rad s^{-1}); some unloading can occur if the subject does not control the eccentric muscle action and moves away from the load at higher speeds. No eccentric muscle actions were tested in this study but reciprocal concentric–eccentric muscle actions were performed with low loads during the fatigue protocol.

Torque–velocity test

A pilot study consisted of performing maximal efforts at four different isotonic loads (40·6, 54·2, 67·8 and 81·3 N · m or 30, 40, 50 and 60 feet · lb). The subject was asked to produce a maximal effort to move the isotonic pre-loads as fast as possible (Fig. 1). The subject was tested three times at each load and the peak velocity and torque values were recorded, averaged (Fig. 2) and a regression line calculated. Maximal power output occurred at the point representing one-half of the projected maximal velocity and one-half of the projected maximal torque (Fig. 2). The use of regression analysis for this data was verified by testing a few subjects randomly at 12 different loads representing a range of 20–80% of their predicted isometric maximum. During a single testing session, the subject was asked to stand up after each set of four loads while the data were calculated and the dynamometer reset for the next four tests. After being seated again, the tests were continued; the data were linear (Fig. 3) over the range of loads tested.

Test criteria

During the pilot study, test criteria were developed. Women were tested and regression lines were calculated for the torque–velocity results ranging from 27·1 to 81·3 N · m (20–60 feet · lb). To be acceptable, the

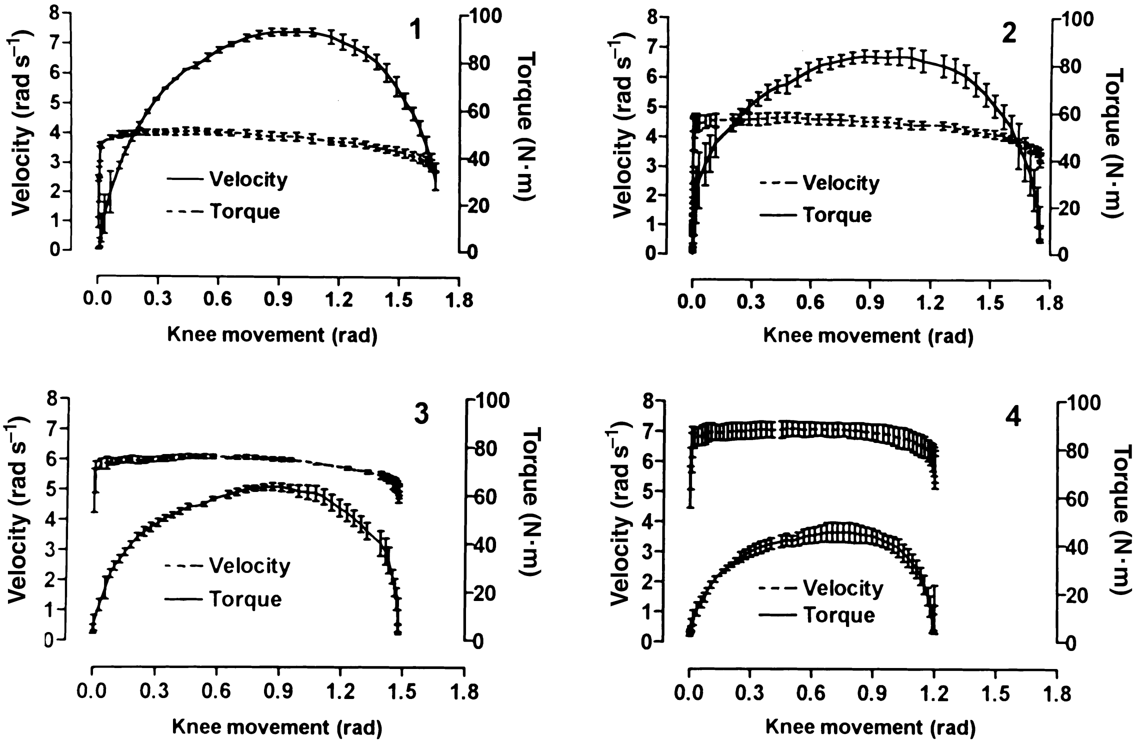

Figure 1 Velocity and torque as a function of knee movement for four different loads (40·6, 54·2, 67·8, 81·3 N · m). Zero degrees of knee position equals the start position for the movement or 1·745 rad (100°) of knee flexion. Data are presented as mean ± standard deviation for three maximal efforts.

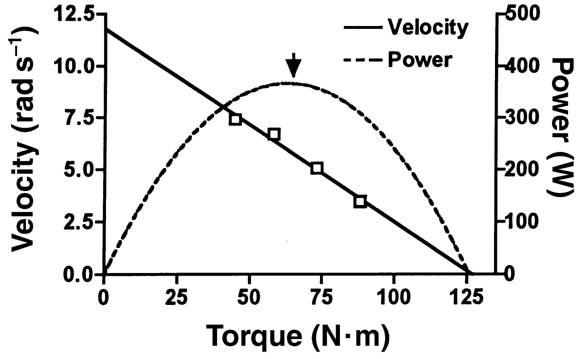

Figure 2 Torque–velocity and torque–power relationships. The squares represent the maximal velocities of knee movement at each of the four loads for one subject. The data are presented as mean ± standard for three maximal efforts. Power was calculated from the torque–velocity data. The arrow indicates calculated maximal power.

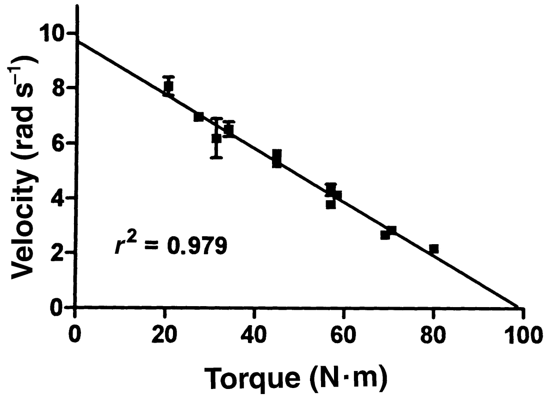

Figure 3 Torque–velocity relationship for 12 different loads selected at random for one subject. The data are presented as mean ± standard deviation for three maximal efforts.

torque–velocity test for the women was to use loads of 27·1, 40·6, 54·2, 67·8 N · m (20, 30, 40 and 50 feet · lb) and have an r^2 value ≥0·95 for the regression line. All 28 subjects met the test criteria.

Fatigue protocol

The fatigue protocol was established by trial and error using maximal efforts and beginning after a

4 min rest. The test consisted of three bouts of 15 repetitions incorporating reciprocal concentric and eccentric muscle actions using a 33·9 N · m (25 feet · lb) load. The activity was limited to 15 repetitions as most individuals found it difficult to continue due to fatigue and muscle pain (burning). The timing was left to the individual but was approximately one movement every second. Each bout was separated by a 15 s rest period which was approximately the time of the exercise and sufficient for cessation of pain. Total positive work (load × distance in joules for concentric muscle actions) and average power (Watts) was calculated for each bout. A second torque–velocity test was performed after a 4 min rest to allow for recovery of dynamic function (Sargeant & Dolan, 1987) and to set-up the testing parameters and print out the data. The entire testing time for each subject was less than 15 min.

Data analysis

Torque (N · m), angular position (radians) and velocity (rad s^{-1}) were measured by two methods. Method 1 used the data produced by the computer interfaced with the dynamometer which sampled the signals 100 times per second. In order to verify the accuracy of the Dynatrac data and power calculations, an independent recording system was used. In method 2, the unprocessed electrical signals for angular position, torque and velocity were sent to a separate data acquisition system using a DT717 data acquisition board (Data Translation, Marlboro, Massachusetts, USA) connected to a 33 MHz 30486 personal computer sampling at 120 kHz. The data were processed by the Global Lab data acquisition and analysis software (Data Translation). Both systems were operational for the same test which allowed comparison of data and data analysis. The two methods of data acquisition gave identical results (Table 1). Thus, the dynamometer's data output could be used for data analysis and power calculations which simplified the testing.

Statistical analysis and linear regression were performed using Prism 2 software (GraphPad, San Diego, California, USA). Paired *t* tests were performed on the two power tests (before and after fatigue). The Tukey–Kramer multiple comparison test was used on the work results for the three bouts of fatiguing exercise.

Table 1 Regression analysis for the two methods of data collection.

	Method 1	Method 2
Number of test points	4	12
y intercept (rad s^{-1})	10·70	10·63
x intercept (N · m)	150·4	150·5
Slope	−5·5	−5·4
r^2	0·998	0·978
Maximal power (W)	402·5	403·4

Results

Under the conditions of the test, a linear torque–velocity relationship was produced for each subject (Figs 2 and 3). From the torque–velocity results, a torque–power relationship could be calculated (Fig. 2). Since the maximal power occurred at a point where the torque and velocity were 50% of maximum, a calculation for maximal power could be made from the regression analysis without requiring a test of each subject at the exact load corresponding to their maximal power output (Table 1). The variability of the testing was quite small (Table 2), generally less than 5% for the independent variable (velocity).

During the fatigue protocol, the peak power declined (Figs 4 and 5) due to a decrease in maximal velocity. Total positive work for concentric muscle actions was also less (Fig. 6) due to a decrease in range of motion (i.e. terminal knee extension). Recovery of maximal power after a 4 min rest was variable (Figs 7 and 8). For the entire group, an average recovery of 85% in maximal power was calculated, with individuals ranging from about 70–99%.

Two subjects (A & B), with nearly identical physical characteristics, demonstrated the extreme examples seen. Both subjects had almost identical pre-fatigue maximal power (i.e. 438 and 442 W, respectively) and similar predicted isometric force as derived from the torque–velocity relationship (i.e. 134 and 145 N · m). It was also evident that both subjects began the fatigue protocol at about the same peak power output (i.e. approximately 400 W). Subject A was able to recover to the starting peak power after each rest period of 15 s (Fig. 4), while subject B lost power throughout the entire fatigue protocol (Fig. 5). The final outcome was also different for the two subjects (Figs 7 and 8). Subject A recovered almost

Table 2 Analysis of the coefficient of variance for velocity.

Load number	Torque (N·m)	Test 1		Test 2	
		Velocity (rad s^{-1})	CV	Velocity (rad s^{-1})	CV
1	27·1	8·51 ± 0·98	2·3 ± 1·0	8·01 ± 0·80	2·0 ± 1·2
2	40·6	7·75 ± 0·87	1·8 ± 1·3	7·10 ± 0·80	2·1 ± 1·1
3	54·2	6·75 ± 0·89	2·1 ± 1·1	5·97 ± 0·82	2·4 ± 1·5
4	67·8	5·77 ± 0·79	2·2 ± 1·3	5·02 ± 0·87	3·2 ± 1·6

Coefficient of variance (CV) = (standard deviation/mean) × 100. Test 1, before fatigue protocol; test 2, after fatigue protocol. Values are means ± standard deviation (n = 28).

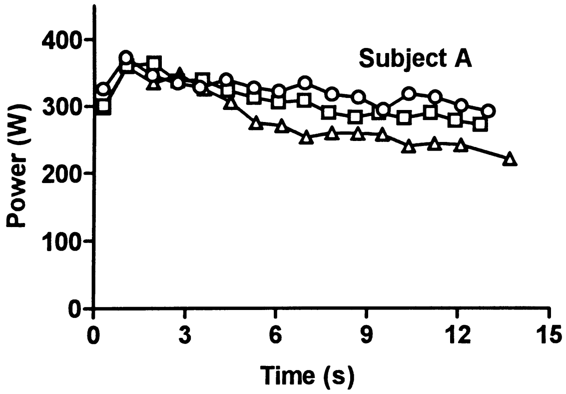

Figure 4 Power as a function of time for the three bouts of dynamic exercise which comprised the fatigue protocol for subject A. (○) bout 1; (□) bout 2; (△) bout 3.

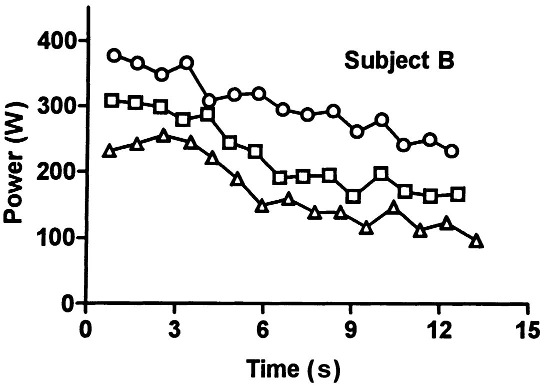

Figure 5 Power as a function of time for the three bouts of dynamic exercise which comprised the fatigue protocol for subject B. (○) bout 1; (□) bout 2; (△) bout 3.

completely to her pre-fatigue power output (412 W) but subject B recovered only 70% of her knee extensor power output (304 W) following the 4 min rest period.

For the group as a whole, the before and after fatigue results are presented in Tables 2 and 3. The frequency distribution histogram for the maximal power output is presented in Fig. 9.

Discussion

Methodological considerations

The present study focused on establishing strict test criteria for evaluating the outcome of an acute fatiguing exercise on muscle power. The study documents the variability in the recovery of maximal power of the knee extensors in college-aged females. The ease of testing using sub-maximal isotonic pre-loads to evaluate muscle power and fatigue will allow similar measurements to be made for sports and occupational tasks where maximal loads are seldom experienced but where maximal isometric or isokinetic strength continues to be used for assessment (Chaffin, 1975).

Previously, the effect of fatigue on dynamic muscle functioning of the knee extensor muscles has been evaluated primarily with isokinetic testing (Vandervoort *et al.*, 1990). Isokinetic dynamometers, including cycle ergometers, control the angular velocity and allow the force (torque) to vary as muscle output changes. The use of an isotonic loading device in this study allowed measurement of the maximal angular velocity during a movement where the muscles were loaded during both acceleration and deceleration. Acceleration and deceleration of extremities are part of normal human movements (Marras, 1992) but generally occur under load. The peak velocity was recorded at around 1 · 05 radians (60°) of knee flexion (Fig. 1), where the maximal force for such a dynamic

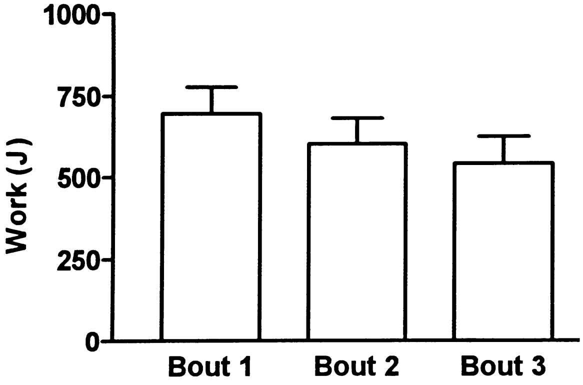

Figure 6 Total work performed during the concentric muscle actions of the three bouts of dynamic exercise which comprised the fatigue protocol. Data are presented for the entire subject population as mean ± standard deviation.

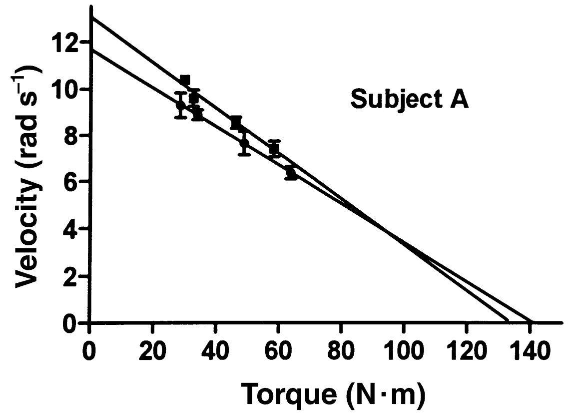

Figure 7 Torque–velocity data for subject A. (■) before fatigue protocol; (●) after fatigue protocol. Data are presented as mean ± standard deviation.

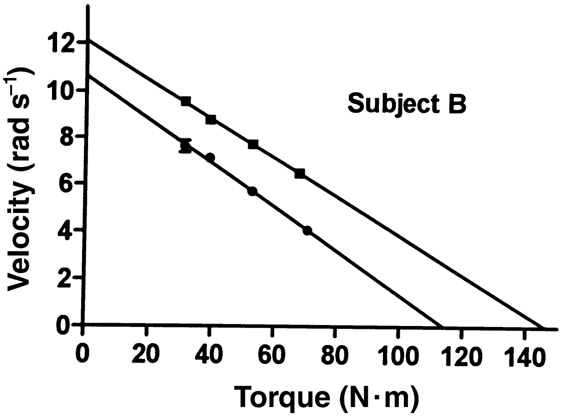

Figure 8 Torque–velocity data for subject B. (■) before fatigue protocol; (●) after fatigue protocol. Data are presented as mean ± standard deviation.

Table 3 Calculated data.

	Power (W)	Slope	r^2
Before fatigue protocol	408 ± 56	−5·9 ± 1·5	0·98 ± 0·01
After fatigue protocol	345 ± 48*	−6·8 ± 1·6	0·98 ± 0·02
Percentage difference	14·9 ± 8·3		

* P<0·001. r^2 ('goodness of fit') calculated for torque–velocity data.

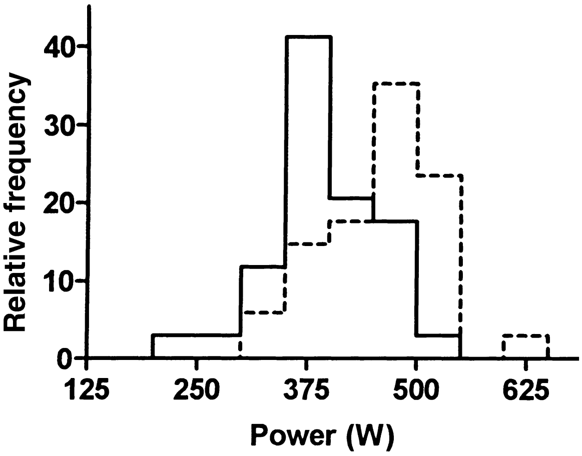

Figure 9 Relative frequency histogram for maximal power output of all subjects. Dashed line, before fatigue protocol; solid line, after fatigue protocol.

movement was expected. This peak velocity remained in this range during the fatigue protocol, even when the entire range of motion was decreasing. Thus, dynamic testing using isotonic loading demonstrated two commonly experienced functional outcomes of fatigue: (1) decreased range of motion, and (2) decreased speed of movement.

The relationship between peak velocity and isotonic pre-load (torque) was linear over the range of loads tested (r^2 > 0·98). The reason for this linear relationship is not clear but is often reported by others using isokinetic dynamometers for measuring knee extension (Caiozzo *et al.*, 1981; Fugl-Meyer *et al.*, 1982; Harries & Bassey, 1990; Vandervoort *et al.*, 1990; Berg *et al.*, 1991; Dudley *et al.*, 1992; Gulch, 1994) and cycling (McCartney *et al.*, 1983; Beelen & Sargeant, 1991). We have tested one individual at 20 different loads and all the velocity values were on the regression line (Stauber and Weiland, unpublished observations), and several individuals with 12 different loads representing about 20–80% of their maximum predicted isometric load (Fig. 3). Although it is generally accepted that a hyperbolic fit best describes the muscle mechanics (Wickiewicz *et al.*, 1984; Dudley *et al.*, 1990; Sale, 1991), Perrine & Edgerton (1978) presented data and arguments based on physiological mechanisms for a linear relationship between torque and velocity of the knee extensors tested *in vivo*.

Since the testing requires holding a pre-load and then quickly changing the output of the muscles over a short distance, both myofibre physiology and neural control factors determine the peak velocity and power. This type of muscle action closely matches functional activities. Namely, a muscle is active and then rapidly brought to a higher level of activation in a short time. The shortening of a muscle under an isotonic pre-load for a short time differs from the 'quick release' isotonic methods used to study isolated muscles. The 'quick release' requires that the muscle be maximally active before the shortening begins (Hill, 1938); practically, this would require co-contraction of the antagonist muscles prior to the initiation of movements. Thus, while our testing protocol is functional, it would under-estimate the absolute maximal velocity of the knee extensor muscles at low loads tested under non-functional, ideal laboratory conditions.

With this limitation in mind, the validity of our calculation to predict the maximal functional velocity and maximal isometric strength was tested by comparisons with published data on the maximal velocity and isometric torque of the knee extensors in young women. The y intercept (11.0 ± 1.5 rad/sec) calculated from our data was only marginally smaller (9%) than that reported for females using a device with a very low moment of inertia (12.0 ± 0.3 rad/sec) (Harries & Bassey, 1990). The x intercept (150 ± 26 N · m) was also less than the left leg isometric torque (163 ± 7 N · m) calculated as 90% of the right side (Digby Sale, personal communication). For the right leg, the isometric torque measured at 60° of knee flexion from similar aged females was 180 ± 7 N · m (Murray *et al.*, 1985). Subsequent analysis of data from many studies (Fig. 10) demonstrated that our test protocol would predict both maximal velocity and maximal isometric torque within 10% as well as low-speed isokinetic torque (45, 60 degrees s^{-1}) using different dynamometers (Vandervoort *et al.*, 1990; Eickhoff *et al.*, 1993).

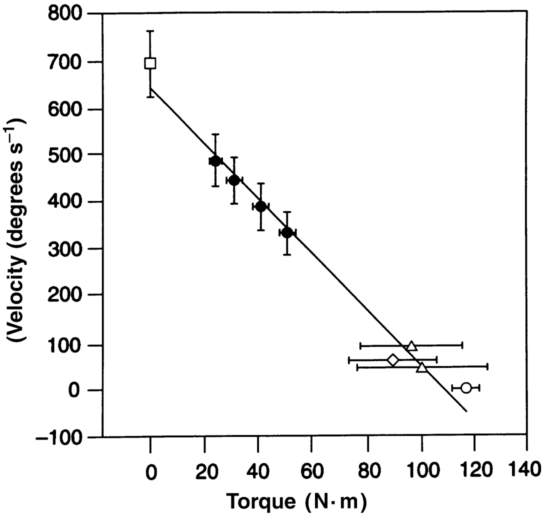

Figure 10 Torque–velocity data for all our subjects ($n = 28$) and from published data (reported in degrees s^{-1}). (●) Pre-fatigue data, current study; (□) data from Houston *et al.* (1988); (△) data from Westing *et al.* (1990); (◇) data from Eickhoff *et al.* (1993); (○) data calculated from Murray *et al.* (1985).

Physiological considerations

When fatigue is produced by high-intensity voluntary dynamic movements, there is a variable amount of loss of power in college-aged females. Subjects with identical power may have remarkably different performance characteristics which may reflect fundamental differences in physiology or chemistry (Enoka & Stuart, 1992). There was a trend for untrained women with higher power output to demonstrate greater declines in power after a short bout of high-effort dynamic exercise, but exceptions were common. Although fibre typing was not performed, the results appear, at first, to be consistent with the biological significance of muscle fibres. Fast-twitch (type II) fibres produce the most power but fatigue most easily (Sargeant, 1994).

In human muscles which are composed of mixed fibre types (i.e. most muscles), all types of fibres would be expected to contribute to maximal voluntary efforts. Since the type II muscle fibres are the fastest and contribute most to maximal power production (Sargeant, 1994), a change in slope in the torque–velocity test was expected following the fatigue protocol, but no such change occurred. Therefore, fatigue of type II muscle fibres must affect both force and maximal velocity to the same extent (Fig. 8). This finding is in contrast to the results seen in cycling where the high-velocity cycling rates were most reduced following 6 min of maximal cycling effort (Beelen & Sargeant, 1991). Considering the duty cycle of the leg muscles during cycling, creatine phosphate and lactate levels should be returning towards resting levels by 6 min as aerobic metabolism predominates (Hultman & Spriet, 1986). In our fatigue protocol, the quadriceps muscles of one leg were maintained maximally active for both concentric and eccentric muscle actions for three bouts of 15 s. This level of muscle contraction would reduce blood flow and stress anaerobic pathways leading to metabolite accumulation (e.g. H^+, $H_2PO_4^-$) (Miller *et al.*, 1988; Schott *et al.*, 1995). Thus, recovery from our fatigue protocol may reveal individual differences in muscle chemistry (e.g. buffering capacity) or bio-energetics (e.g. phosphagen stores, energy utilization and re-synthesis) rather than differences in fibre type physiology (Vandervoort *et al.*, 1990). The differences in power decline and recovery seen in our study (Figs 4 and 5) were similar to the individual differences in creatine phosphate consumption and re-synthesis reported for ischaemic exercise and recovery using ^{31}P nuclear magnetic resonance spectroscopy (Blei *et al.*, 1993). Therefore, differences in bio-energetics may account for the individual variation in recovery of muscle power from our fatigue protocol – an area which requires further study.

Fatigue

Fatigue, defined as a time-dependent loss in maximal power output, did not depend on the initial level of power output, although more powerful individuals tended to lose more power. Similarly, initial strength, as assessed by isokinetic testing, was shown not to predict isokinetic endurance (Larsson & Karlsson, 1978; Mathiassen, 1989), even though reports to the contrary exist (Costill *et al.*, 1979; Clarkson *et al.*, 1982). Furthermore, isokinetic testing may be contraindicated for the frail elderly and patients with joint pain because of their intolerance to high joint forces (Nisell *et al.*, 1989; Kaufman *et al.*, 1991).

Quick and safe testing of diverse populations, including those with sports injuries, can now be accomplished using sub-maximal loads to measure maximal power output, with the added benefit of estimating maximal isometric and isokinetic strength. Since little is known about alterations in human muscle power following training, surgery, injury, immobilization or with ageing, this simple testing protocol should have wide application.

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References

ARVIDSSON I., ERIKSSON E., KNUTSSON E. & ARNER S. (1986) Reduction of pain inhibition on voluntary muscle activation by epidural analgesia. *Orthopedics*, **9**, 1415–1419.

BEELEN A. & SARGEANT A. J. (1991) Effect of fatigue on maximal power output at different contraction velocities in humans. *J Appl Physiol*, **71**, 2332–2337.

BERG H. E., DUDLEY G. A., HAGGMARK T., OHLSEN H. & TESCH P. A. (1991) Effects of lower limb unloading on skeletal muscle mass and function in humans. *J Appl Physiol*, **70**, 1882–1885.

BLEI M. L., CONLEY K. E., ODDERSON I. B., ESSELMAN P. C. & KUSHMERICK M. J. (1993) Individual variation in contractile cost and recovery in a human skeletal muscle. *Proc Natl Acad Sci USA*, **90**, 7396–7400.

CAIOZZO V. J., PERRINE J. J. & EDGERTON V. R. (1981) Training-induced alterations of the *in vivo* force–velocity relationship of human muscle. *J Appl Physiol*, **51**, 750–754.

CHAFFIN D. B. (1975) Ergonomics guide for the assessment of human static strength. *Am Ind Assoc J*, **36**, 505–511.

CLARKSON P. M., JOHNSON J., DEXTRADEUR D., LESZCZYNSKI W., WAI J. & MELCHIONDA A. (1982) The relationships among isokinetic endurance, initial strength level, and fiber type. *Res Q Exerc Sport*, **53**, 15–19.

Costill D. L., Coyle E. F., Fink W. F., Lesmes G. R. & Witzmann F. A. (1979) Adaptations in skeletal muscle following strength training. *J Appl Physiol*, **46**, 96–99.

Dudley G. A., Harris R. T., Duvoisin M. R., Hather B. M. & Buchanan P. (1990) Effect of voluntary vs. artificial activation on the relationship of muscle torque to speed. *J Appl Physiol*, **69**, 2215–2221.

Dudley G. A., Duvoisin M. R., Adams G. R., Meyer R. A., Belew A. H. & Buchanan P. (1992) Adaptations to unilateral lower limb suspension in humans. *Aviat Space Environ Med*, **63**, 678–683.

Edgerton V. R., Roy R. R., Gregor R. J. & Rugg S. (1986) Morphological basis of skeletal muscle power output. In: *Human Muscle Power* (ed. Jones N. L. N., McCartney N. & McComas A. J.), pp. 43–64, Human Kinetics Publishers, Inc., Champaign, Illinois.

Eickhoff J. A., Molczyk L., Gallagher J. C. & De Jong S. (1993) Influence of isotonic, isometric and isokinetic muscle strength on bone mineral density of the spine and femur in young women. *Bone Miner*, **20**, 201–209.

Enoka R. M. & Stuart D. G. (1992) Neurobiology of muscle fatigue. *J Appl Physiol*, **72**, 1631–1648.

Fugl-Meyer A. R., Mild K. H. & Hornsten J. (1982) Output of skeletal muscle contractions. a study of isokinetic plantar flexion in athletes. *Acta Physiol Scand*, **115**, 193–199.

Gulch R. W. (1994) Force–velocity relations in human skeletal muscle. *Int J Sports Med*, **15** (Suppl. 1), S2–S10.

Harries U. J. & Bassey E. J. (1990) Torque–velocity relationships for the knee extensors in women in their 3rd and 7th decades. *Eur J Appl Physiol*, **60**, 187–190.

Hill A. V. (1938) The heat of shortening and the dynamic constants of muscle. *Proc R Soc London [B]*, **126**, 136–195.

Houston M. E., Norman R. W. & Froese E. A. (1988) Mechanical measures during maximal velocity knee extension exercise and their relation to fibre composition of the human vastus lateralis muscle. *Eur J Appl Physiol*, **58**, 1–7.

Hultman E. & Spriet L. L. (1986) Skeletal muscle metabolism, contraction force and glycogen utilization during prolonged electrical stimulation in humans. *J Physiol (London)*, **374**, 493–501.

Kaufman K. R., An K. N., Litchy W. J., Morrey B. F. & Chao E. Y. (1991) Dynamic joint forces during knee isokinetic exercise. *Am J Sports Med*, **19**, 305–316.

Larsson L. & Karlsson J. (1978) Isometric and dynamic endurance as a function of age and skeletal muscle characteristics. *Acta Physiol Scand*, **104**, 129–136.

McCartney N., Heigenhauser G. J. & Jones N. L. (1983) Power output and fatigue of human muscle in maximal cycling exercise. *J Appl Physiol*, **55**, 218–224.

Marras W. S. (1992) Toward an understanding of dynamic variables in ergonomics. *Occup Med*, **7**, 655–677.

Mathiassen S. E. (1989) Influence of angular velocity and movement frequency on development of fatigue in repeated isokinetic knee extensions. *Eur J Appl Physiol*, **59**, 80–88.

Miller R. G., Boska M. D., Moussavi R. S., Carson P. J. & Weiner M. W. (1988) 31P nuclear magnetic resonance studies of high energy phosphates and pH in human muscle fatigue. Comparison of aerobic and anaerobic exercise. *J Clin Invest*, **81**, 1190–1196.

Moritani T. (1992) Time course of adaptations during strength and power training. In: *Strength and Power in Sport* (ed. Komi P. V.), pp. 266–278, Blackwell Scientific Publications, London.

Murphy A. J. & Wilson G. J. (1996) Poor correlations between isometric tests and dynamic performance: relationship to muscle activation. *Eur J Appl Physiol*, **73**, 353–357.

Murray M. P., Duthie E. H. Jr, Gambert S. R., Sepic S. B. & Mollinger L. A. (1985) Age-related differences in knee muscle strength in normal women. *J Gerontol*, **40**, 275–280.

Nisell R., Ericson M. O., Nemeth G. & Ekholm J. (1989) Tibiofemoral joint forces during isokinetic knee extension. *Am J Sports Med*, **17**, 49–54.

Perrine J. J. & Edgerton V. R. (1978) Muscle force–velocity and power–velocity relationships under isokinetic loading. *Med Sci Sports*, **10**, 159–166.

Richards J. G., Quigley E. J., Castagno P. W. & Neeves R. E. (1996) Validity and reliability of the BTE dynatrac. *Med Sci Sports Exerc*, **28**, 913–920.

Sale D. G. (1991) Testing strength and power. In: *Physiological Testing of the High Performance Athlete, 2nd Edn* (ed. MacDougall J. D., Wenger H. & Green H. J.), pp. 21–106, Human Kinetics Publisher, Inc., Champaign, Illinois.

Sargeant A. J. (1994) Human power output and muscle fatigue. *Int J Sports Med*, **15**, 116–121.

Sargeant A. J. & Dolan P. (1987) Effect of prior exercise on maximal short-term power output in humans. *J Appl Physiol*, **63**, 1475–1480.

Schott J., McCully K. & Rutherford O. M. (1995) The role of metabolites in strength training. II. Short versus long isometric contractions. *Eur J Appl Physiol*, **71**, 337–341.

Vandervoort A. A., Kramer J. F. & Wharram E. R. (1990) Eccentric knee strength of elderly females. *J Gerontol*, **45**, B125–B128.

Westing S. H., Seger J. Y. & Thorstensson A. (1990) Effects of electrical stimulation on eccentric and concentric torque–velocity relationships during knee extension in man. *Acta Physiol Scand*, **140**, 17–22.

Wickiewicz T. L., Roy R. R., Powell P. L., Perrine J. J. & Edgerton V. R. (1984) Muscle architecture and force–velocity relationships in humans. *J Appl Physiol*, **57**, 435–443.